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A study of chemical stabilization of the swell properties of Putman soil

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Department:

A STUDY OF CHEMICAL STABILIZATION OF THE SWELL PROPERTIES OF PUTNAM SOIL

BY

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A

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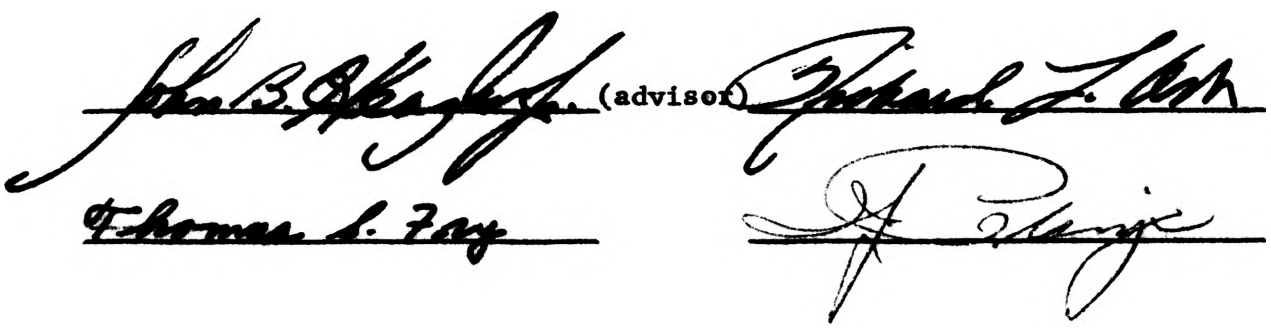

ABSTRACT

The theory of chemical stabilization of a swelling clay was reviewed. The effect of several chemicals on the engineering properties of Putnam soil was investigated using the Atterberg tests. Strength of concentration of chemical additives versus preferred structural orientation of treated Putnam was investigated using sedimentation procedures similar to those used in the hydrometer analysis of fine grained soil sizes. Swell tests were conducted under a static load of 1.25 psi on untreated Putnam, Putnam in combination with sodium carbonate, and Putnam treated with calcium hydroxide. These tests were conducted at varying initial moisture contents and dry densities.

It was found from the swell tests that the measured swell of Putnam under the load used was uniquely related to the initial moisture content of the sample.

ACKNOWLEDGMENT

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

This manuscript describes the results of a study made to determine the effects of a few selected chemical additives on the swell properties of soil pedologically classified as Putnam silt loam. Putnam silt loam covers an extensive portion of northeast Missouri and presents very serious problems to engineers and the construction industry in that area. This type of soil is described in a Missouri State Highway Department publication[1] as, "One of the poorest soils commonly encountered in Missouri highway construction...notorious for its volume change, which averages at least 60 per cent and often runs as high as 75 per cent. Proper use of it in construction is further complicated by its physical characteristics, topography, etc." Modification of the volume change characteristics would undoubtedly result in considerable savings in both initial construction costs and in maintenance.

To the layman it might seem that the scientific way to approach a study of this type would be for an expert chemist to make a thorough investigation of the basic material and, based upon his findings, select the chemical for the job. This approach is not practical or in some cases even possible because soil, particularly clay soil, is an extremely heterogeneous and complex substance and the probable results of various chemical additives are subject to considerable controversy until they are tested in the laboratory. The complexity of chemical treatment together with the tremendous potential market for chemical stabilizing agents in the highway construction industry has attracted many chemical manufacturers into initiating extensive research programs in this field and it may be just a question of time until today's methods and techniques of soil

stabilization, particularly chemical soil stabilization, are vastly altered by their efforts. It will remain for the civil engineer, however, to evaluate the feasibility of these new stabilization techniques and supervise their utilization.

When attempting to stabilize any particular soil, the civil engineer is not as interested in the chemical results as he is in the resultant change in the engineering properties. In other words, the chemist may find particular chemicals which might offer promise in the field of soil stabilization, but the civil engineer will be the ultimate judge of their real value. Therefore, it follows that this particular study is not a chemical study but a civil engineering approach to a civil engineering problem.

In attempting to alter any soil chemically, the best and most logical approach is to start with the most promising additive and continue from there. The discovery of a successful additive represents a significant achievement in itself, however, economic considerations often necessitate a search for a better answer.

The stabilization of Putnam silt loam is in this stage today. Chemicals have been found which will improve the engineering properties of this soil, however, these are not entirely satisfactory and a better means of treating this soil is needed.

Because of the complexity of the material and difficulty in predicting results, it was fully appreciated at the outset of this work that the ideal stabilization agent would probably not be found. The specific intention was to devise and initiate a much needed program of extensive research on this problem soil. In line with this idea, the major objectives of this investigation were to:

1. Critically review some of the existing literature on the swell properties of natural soils and evolve a basic concept from which to approach the stabilization of Putnam silt loam.

2. Conduct a study of some of the basic properties of Putnam silt loam.

3. Devise and evaluate expeditious methods of comparing the effects of various chemical additives on the swell properties of a given soil.

4. Determine the effect of a number of different additives on some of the basic properties of Putnam silt loam.

5. Measure the effects of selected chemicals on the swell properties of Putnam silt loam in order to evaluate the derived concept regarding the stabilization of this soil.

The study was limited to investigating the swell produced in a sub-base under a restrictive pressure of 1.25 psi. Limitation of the restrictive pressure to one value was necessary in order to reduce the magnitude of laboratory work involved. The value chosen corresponds to 1.25 to 1.50 feet of burden and approximates the restrictive pressure at nine to twelve inches below a highway slab. The swell in this area (or perhaps slightly higher) is the primary cause of difficulty encountered in road construction and maintenance. Swell below this level could be eliminated by any similar chemical treatment to a depth at which the burden of overlying material would compensate for the swell pressures. Swell above this level is eliminated in most cases by the necessity of utilizing select material for the base and surface courses.

II. REVIEW AND DISCUSSION OF LITERATURE

The use of soil stabilization is not new in the field of civil engineering; however, its range of application has been vastly enlarged in recent years due to the tremendous advances made in the field. Because of this, the term indicates different things to different people and, therefore, a brief outline of the scope of the science is felt appropriate.

Heagler[2] in his course notes states, "The term soil stabilization as used by engineers is aptly defined as any treatment of an earthen material which will improve its physical properties to satisfy more nearly a particular engineering requirement." It is the opinion of this writer that, "Any treatment", in the above quotation should be taken in its most literal sense. To emphasize this point and illustrate the scope of the science, most authorities catagorize the various methods of improving soil characteristics. The enumerations vary greatly in terms used; however, they all generally define the same boundaries. Murray[3] catagorizes the methods of stabilization as simply any physical or chemical treatment. He further divides chemical treatment into the following classes:

> "1. Those treatments in which the effect of the chemical is essentially due to its interaction with the soil and in which the physical properties of the chemical itself play little, if any, role.
>
> 2. Those treatments in which the effects of the additive are due both to its interaction with the soil and to its own physical properties.
>
> 3. Those treatments in which the effect of the stabilizing agent are due essentially to the properties of the additive itself and in which interaction with the soil plays little, if any, role."

Regardless of terms used, it is a basic truth that soil stabilization is concerned mainly with the control of moisture in soil. Michaels[4] states, "A review of the extensive literature on the subject of soil leads to the rather significant observation that nearly all problems associated with the use, manipulation, and treatment of soils arise from the effects upon soil properties of the presence (and occasionally, absence) of water. In essence at least, the major objective of soil stabilization is to develop methods of treating soils so that they retain desired properties irrespective of the wetness or dryness of their environment."

In the stabilization of clay soils, the control of moisture is of particular importance and is much more complex than in coarse-grained soils. When treating clay soils, moisture, clay structure, and the properties of the mineral as well as the adsorbed ions and water, play a complex and interrelated part in determining the engineering characteristics of the soil mass. These characteristics have been the subject of a tremendous amount of study in recent years by several of the leading authorities in the field of soil mechanics and clay minerology. Since this manuscript deals with the attempted stabilization of a clay soil, an understanding of some of the basic properties of a clay mineral is necessary.

The montmorillonite clay crystal is made up of three layers: Two tetrahedral (silica) layers, with an octahedral (alumina) layer sandwiched in between (figure 1). The isomorphic substitution of bivalent ions, such as iron or magnesium, for some of the trivalent aluminum ions in the octahedral layer creates an excess negative charge which in turn results in a free surface energy. To satisfy the valence demand

brought about by the substitution of lesser valence ions, cations and water (due to its bi-polar property) are adsorbed on the basal surfaces.

Figure 2 depicts how the surface potential caused by the broken bonds at the edge of the crystal (fracture zone, figure 1) is satisfied. The "Rigid layer" shown is primarily made up of adsorbed water and anions and is essentially immovable by hydrodynamic means.[5] It results in a negative surface. This is satisfied by the adsorption of cations which are attracted towards the negatively charged surface and form a "Diffuse layer" of positive charges, "In a manner analogous to the way in which the atmosphere of the earth is retained by gravitational forces."[6] The cations thus adsorbed and their accompanying water of hydration are more firmly held near the edge of the particle. This attraction decreases exponentially towards the extremity of the diffuse layer. This decrease in attraction is termed "Zeta potential" as shown.

Just how the attraction for moisture would effect the energy characteristics of a clay mineral can be rather dramatically illustrated in the case of a clay containing an abundance of sodium ions in the diffuse layer. Sodium, which is a large ion to begin with (0.98 angstroms), is tremendously hydrophillic and when its thirst for water is satisfied, its size swells to approximately 8.0 angstroms. If an abundance of small polyvalent hydrophobic cations were introduced into solution with this soil and an ion exchange resulted, it can readily be seen that the diffuse layer would decrease in size a tremendous amount. Further, the base exchange capacities, which are a measure of the quantity of adsorption positions available, of some of the clay minerals are listed as: Illite 10-40, Montmorillonite 80-150, and Kaolinite 3-15 milliquivilents per 100 grams of soil.[10] Thus, the base exchange

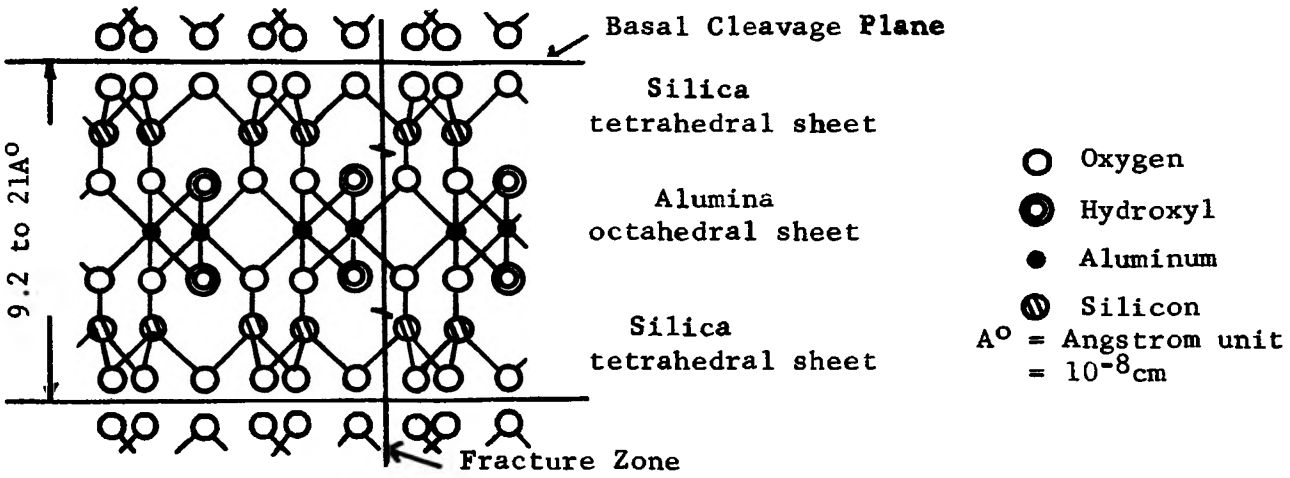


Figure 1 MONTMORILLIONITE CLAY CRYSTAL (7)

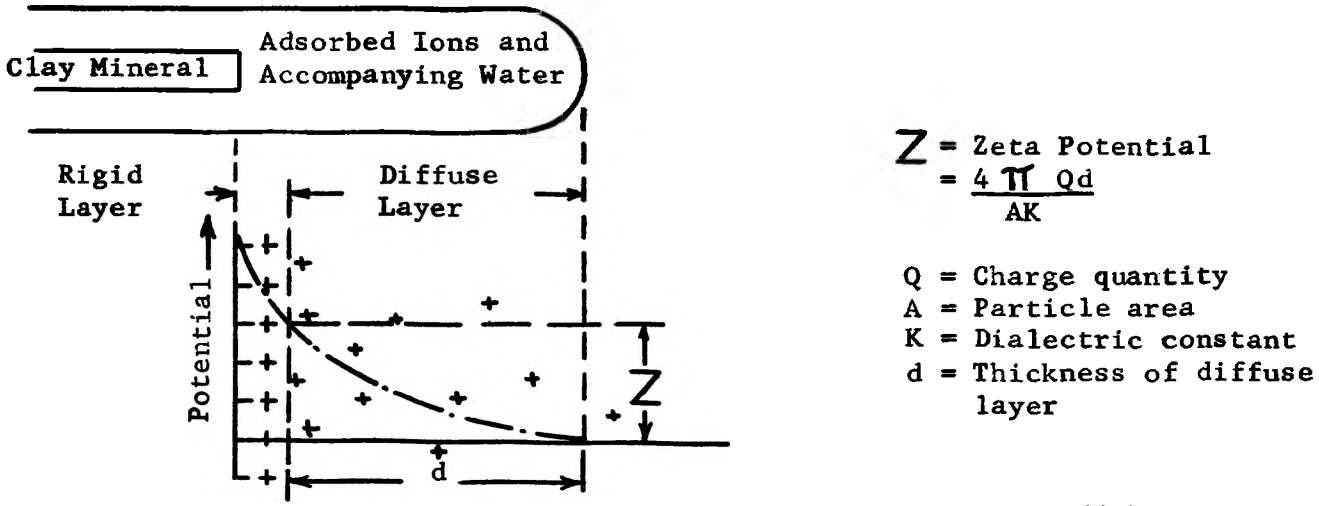


Figure 2 DECREASE IN POTENTIAL WITH DISTANCE FROM THE SURFACE (8)

Deflocculent (High Energy)

Increase	---	Plasticity -----	Decrease
Decrease	---	Friction -------	Increase
Increase	---	Cohesion -------	Decrease
Increase	---	Shrinkage ------	Decrease
Increase	---	Density --------	Decrease
Decrease	---	Permeability ---	Increase
Decrease	---	Friability -----	Increase

Flocculent (Low Energy)

Figure 3 PHYSICAL PROPERTIES GENERALLY ASSOCIATED WITH SOIL STRUCTURE (9)

capacity of a particular mineral, coupled with the type of cations adsorbed, greatly influence the energy system of the various minerals with a resultant effect on the soil's engineering characteristics (figure 3). The need for identifying and understanding the properties of a particular mineral should be readily apparent.

The attractive property of clay for water has been illustrated. This attraction is paramount in determining the resultant engineering properties and manifests itself by affecting the resultant soil structure. Soil scientists have long agreed that clay with large diffuse layers (high surface potential) tend to form deflocculent structures, while the systems with small diffuse layers (low surface potential) tend to form flocculent structures. The type of structure will in turn dictate to a very large degree the resultant engineering properties of a given soil (figure 3). An important principle here is that these properties are caused by the original surface potential of the clay mineral.

While this surface potential is the primary cause of the swell characteristics of some clays, it gives rise to other forces which are also of major importance in causing swell. The higher ionic concentration in the vicinity of the clay particles as compared with the porewater creates an osmotic pressure difference, which in turn causes a tendency for water to flow from the area of low concentration to the area of high concentration. In partially saturated soils, the affinity of soil for water together with the surface tension of water results in curved air-water interfaces which create a pressure differential and an attraction for additional water. In compacted partially saturated clays, entrapped air is sometimes the cause of disruptive forces causing swell and has been suggested as the cause of slaking when a dry sample is immersed in water.

Also some clay swelling can be attributed to unbending of strained clay particles. These related physico-chemical and mechanical causes of swell are well discussed by Seed.[11] It is again pointed out, however, that the attraction of the clay surface for water and cations and their water of hydration is the primary cause of most of these other forces.

At this point it is rather obvious that the role water plays in a swelling clay is somewhat complex. When the fact that the clay soil itself is also complex, and evaluation of the cause of swell of a particular soil is difficult, then the controversies regarding some of the theories of how best to treat a swelling clay soil are understandable.

Further aggravating this picture is the failure of some authors to emphasize the relationship of swell to the surface energy. An example of this is an article by Seed[12] illustrating the volume change characteristics of clay soils in terms of soil structure which he relates only to compaction methods, compactive effort, and moisture content.

One means of bringing the whole subject into better focus is to approach it from an energy concept.[13] Under this concept, it would be best to place a soil so that it is in a state of equilibrium. That is to say, that it assumes its preferred structure and that its thirst for water and cations is satisfied. Soils placed other than in a state of equilibrium would (barring outside influences such as confining pressures, water barriers, etc.,) return to its equilibrium condition or at least have a tendency to do so. This would result in a volume change. The apparent volume change may be adjusted by controlling the placement density thus compensating for an actual volume change of individual soil particles within void spaces in the soil. From this concept many of the phenomena regarding volume change characteristics are readily explained.

In line with this theory, control of the swell tendency of a soil by manipulation of the compactive effort, compactive method, or moisture content, may produce some favorable results, however, if the soil is not placed in its preferred structure or at its preferred moisture content, then it will ultimately change, or at least have that tendency. So it depends not so much on what the placement structure or moisture content is but rather what the placement structure and moisture content are with regard to the preferred structure and moisture content.

Considering again the engineering properties enumerated in figure 3, it can readily be seen that for most purposes the flocculated structure is preferable. If the soil to be stabilized has a deflocculated tendency (high energy system), to try and make it behave like a flocculent system by physical manipulation into that type of structure is a temporary measure at best. Barring a chemical treatment, the only logical way to treat this soil is to place it in a state of equilibrium which would amount to a deflocculent structure in a fairly wet state. This would tend to solve its swell characteristics or at least the apparent swell characteristics, but referring to the other resulting properties listed in figure 3, it can readily be seen that it certainly does not improve its engineering properties in general. The best way to describe a soil thus treated is that it is a sticky gooey mess. While this is not very scientific terminology, it is nevertheless very descriptive.

A far superior way to handle this soil is to alter the means by which the surface potential of the clay mineral is satisfied; lower the zeta potential, and thereby produce a tendency for the soil to flocculate. Under the energy concept, in order to place the soil in an equilibrium condition, the soil is best placed at a lower moisture content and in a

flocculent type of structure. This is a far better soil to handle either in the laboratory or in the field and its engineering properties are vastly improved as is demonstrated in Chapter IV. This change is readily accomplished by chemical treatment.

In discord with the principle of flocculation is Michaels statement, "Treating soils with sequestering agents which, by removing and complexing with polyvalent ions (eg. calcium, magnesium, etc.) initially held on the particle surfaces, greatly increase the thickness of the solvation-water layers; This results in a marked reduction in inter-particle cohesion or friction, so that individual soil particles are able to move easily under the action of small exterior forces. Soils so treated tend to undergo marked compaction (with appreciable expulsion of free-water) at low loading, to become essentially water impermeable, to liquify at abnormally low water contents, and to shrink much less on drying than normally."[14] This author felt that such a treatment would probably be very detrimental to Putnam and completely impractical from a construction standpoint, but at the same time it might be of academic interest to measure the resultant effects. By so doing, the theory of increasing the energy system of Putnam in an attempt to stabilize it could, with certain reservations, be eliminated from further consideration.

It will be shown in Chapters III and IV that Putnam is essentially a deflocculent system. To start a study of chemical stabilization of its swelling tendencies, and to be able to evaluate the energy concept of stabilization of a swelling soil, some chemicals commonly used in the field of engineering as flocculating and deflocculating agents were selected. A brief description of each one selected is contained in Chapter III.

There has been an abundance of previous research conducted on Putnam which attests to some extent to the problem it presents.

Changes brought about in Putnam by ionic substitution have been investigated.[15] Although the study involved ionic substitution on Putnam in which all the exchangeable ions had been replaced by hydrogen ions and is therefore difficult to relate to the treatment of natural Putnam soils, this work is nevertheless one of the foremost early publications in the field of chemical soil stabilization. The author performed a rather extensive chemical analysis of a sample of Putnam and listed the base exchange capacity as 30.08 milliquivilents per 100 grams broken down as follows: Hydrogen 12.0, calcium 11.6, magnesium 4.5, and sodium 1.4. He further lists the predominent clay mineral as beidellite.

Grim[16] states that, "Recent studies show that a very large amount of this early so-called beidellite is actually a mixture in many cases an interlayered mixture, of illite and montmorillonite." Nevertheless he goes on to list the formulas for beidellite as[17]:

$$(OH)_4(Si_{6.34}\ Al_{1.66})Al_{4.34}O_{20}$$
$$\downarrow$$
$$Na_{.66}$$

or: $(OH)_4(Si_6 \cdot Al_2)Al_{4.44}O_{20}$

$$\downarrow$$
$$Na_{.66}$$

("In each case the balancing external cation has been indicated as Na+ for convenience.")

This type of clay has essentially the same crystalline structure as montmorillonite (figure 1), the difference being that the substitutions take place in the tetrahedral layer rather than in the octahedral layer.

These substitutions are trivalent aluminum ions for tetravalent silica ions. This substitution results in a stronger basal surface attraction than on the basal surface of the montmorillonite crystal because of the charge shortage being nearer the basal surface. The cations preferentially adsorbed on the basal surfaces of beidellite are either potassium or magnesium.[18]

The most economically competitive means of stabilizing the swell and shrinkage characteristics of Putnam clay reported to date are with small additions of hydrated lime[19], or with lime and portland cement in combination[20]. Both of these additives were reported to eliminate swell and shrinkage characteristics in the laboratory at strengths near six per cent based on the dry unit weight, however, neither author actually measured this affect or at least they did not report the results of so doing.

Experiments have been made with fatty quaternary ammonium salts on Putnam[21]. Although the tests were not conducted and the conclusions were not presented in terms commonly used in soil stabilization, these chemicals nevertheless appear very promising in strengths as low as 0.1 per cent of the dry unit weight.

III. PROCEDURES AND SPECIAL EQUIPMENT

In the review of literature, the author attempted to review and clarify some of the pertinent literature and theories in the field of soil stabilization and clay minerology in order to evolve a concept from which to approach the stabilization of Putnam silt loam. The theory to be used and later evaluated in this study is based on an energy concept[13] which hypothesizes that, when dealing with a swelling soil, the soil should be placed in its preferred structure and its demand for cations and moisture should be satisfied.

In order to evaluate the energy concept, selected chemicals were evaluated for their effect on the engineering properties of Putnam. The best flocculating and deflocculating agents thus found were then used to alter the basic properties of Putnam by changing its energy condition. Finally, the swell characteristics of untreated Putnam, flocculated Putnam, and deflocculated Putnam, each placed at varying moisture contents and densities, were measured. The swell characteristics of the soils thus treated were analyzed to facilitate an evaluation of the energy concept of stabilization of a swelling clay.

While this manuscript deals with reducing the swelling properties of Putnam, it would be prudent to also be able to analyze to some extent the resulting effects of the chemical additives on the other engineering properties. No simple tests are better designed as indicators of the engineering properties than are the Atterberg limits (liquid limit, plastic limit, and shrinkage limit). It is evident that volume changes in a soil must take place somewhere between the shrinkage limit and the liquid limit. Therefore, the magnitude of the difference between these limits

is an indicator of swell characteristics although the application of this criteria must be tempered somewhat. The fact that the physical manipulation of the soil during these tests tends to perhaps alter its preferred structure was considered. However, it was still felt that these tests provided a good means of comparison of the various chemical additives.

Since lime produced such spectacular results (figure 9) with this soil, the other additives were limited in quantity to a value equal to six per cent lime. This was deemed advisable in order to keep the quantities within practical limits.

The best flocculating agent and the best deflocculating agent found from the Atterberg tests were each compared on a strength of concentration basis. This test was performed using methods similar to a soil hydrometer analysis in order to compare sedimentation rates of given quantities of soil treated with varying amounts of the different additives.

It is known that the molding moisture content and density are of paramount importance in influencing the apparent swell and swell pressure characteristics.[11] Also the method of compaction plays an important part inasmuch as this influences the resultant structure which in turn affects the apparent behavior of the soil upon exposure to water. Because of this, it was decided to run swell tests at varying moisture contents and densities with both the untreated soil and the soil treated with flocculating and deflocculating agents.

Swell tests were conducted in Hogentogler Public Roads type consolidation apparatus, model S6101-6131 (figure 6). This particular apparatus was specifically designed for consolidation tests rather than swell tests, therefore procedures used are briefly described. The air

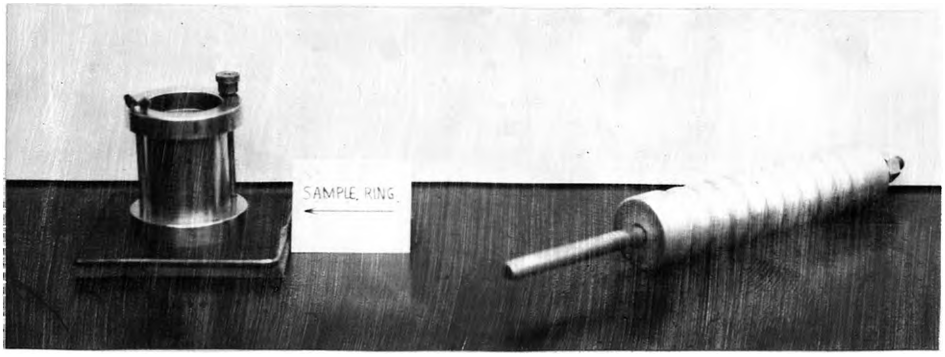


Figure 4 COMPACTION DEVICE AND HARVARD HAMMER

Figure 5 SAMPLE HOLDER ASSEMBLED AND DISASSEMBLED

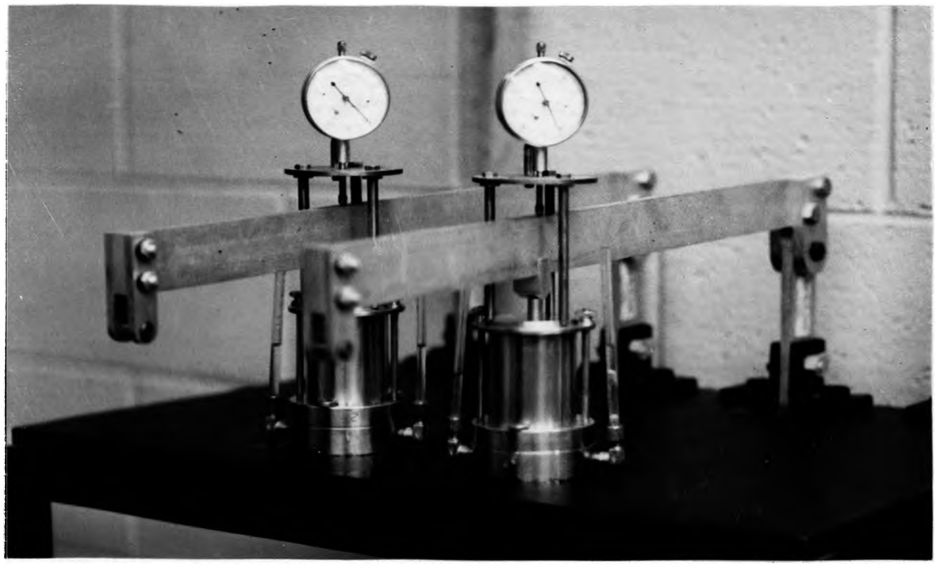


Figure 6 HOGENTOGLER CONSOLIDATION APPARATUS

dry soil was mixed with a pre-determined amount of water and chemical additive based on the calculated oven-dry weight. Mixing difficulty was encountered due to the "balling" tendency of the material, especially when in a high energy (deflocculant) type of structure however, satisfactory uniformity of the moisture was achieved by "chopping" the mud balls until the maximum size was approximately 1/8 inch. The swell sample was made in an assembly specifically designed for this study and compaction was performed with the Harvard hammer (figure 4). After compacting the sample at various densities, the compaction device was dismantled and the ring containing the sample carefully struck off. Any irregularities in the surface were carefully patched by hand until a smooth surface level with the top of the ring was obtained. By this means, all the samples had an area of 18.86 square centimeters, a thickness of 1.44 centimeters and a volume of 27.16 cubic centimeters. The ring containing the sample was then placed in the consolidation apparatus (figure 6) and the predetermined load of 1.25 psi (as explained in chapter I) was applied. Water was then introduced into the system and swelling allowed to commence. Swelling was allowed to continue until there was no noticable volume change in a 24 hour period. The time required for this condition to occur varied somewhat, the maximum time being about three days. Various measurements were taken in order to obtain dry density, per cent swell, initial moisture content, and to provide a check on the degree of saturation after swell had taken place.

The results of all tests are contained in chapter V.

IV. MATERIALS

The sample of Putnam used for this study was obtained from a through-hill cut, 1.6 miles north on State route NN, approximately five miles west of Mexico, Missouri. The sample was taken at a depth of three to five feet below the "A" horizon.

After air drying, the majority of the sample was thoroughly pulverized until it passed the number 40 U. S. Standard sieve. The soil was then allowed to air dry for three days after which it was mixed to obtain maximum uniformity and then stored in galvanized bins.

To aid in the selection of chemical additives and to analyze more intelligently the results obtained, a rather extensive preliminary investigation was conducted, the results of which are presented in table 1. Verbal descriptions of other than standard procedures used in this initial investigation are briefly summarized.

Four grams of sodium hexametaphosphate (commercial "Calgon") were used to obtain a degree of dispersion for the hydrometer analysis. Approximately 0.15 per cent of the sample did not pass the number 10 U. S. Standard sieve, however, this was considered negligible for the purpose of this investigation.

The pH of the sample was obtained on 20 grams of the soil allowed to soak with frequent stirring in 100 cc. of distilled water for about 20 minutes[22]. The Beckman pH meter was used in the determination.

The amount of organic matter in the soil was determined in the manner outlined in the Iowa State College Soil Engineering Laboratory Manual[22]. A portion of the soil was oxidized with potassium dichromate and sulfuric acid, ferrion indicator was added and the solution titrated with standard ferrous ammonium sulphate solution.

CHARACTERISTIC	VALUE	METHOD OF DETERMINATION
pH	6.4	Described in Chapter III
Specific Gravity	2.70	A. A. S. H. O. T100-38[24]
Organic Matter Content	0.34%	Described in Chapter III
Liquid Limit	50.2%	A. A. S. H. O. T89-49[25]
Plastic Limit	19.9%	A. A. S. H. O. T90-49[26]
Plastic Index	32.1%	A. A. S. H. O. T91-49[27]
Shrinkage Limit	11.9%	A. A. S. H. O. T92-42[28]
Unified Classification	CH	(23)
B. P. R. Classification	A-7-6(18)	(23)
F. A. A. Classification	E-8	(23)
B. P. R. Textural Classification	Clay	(29)
X-Ray Identification	Mica Montmorillonite (Tentative)	Described in Chapter III

Table I RESULTS OF INITIAL INVESTIGATION OF UNTREATED PUTNAM

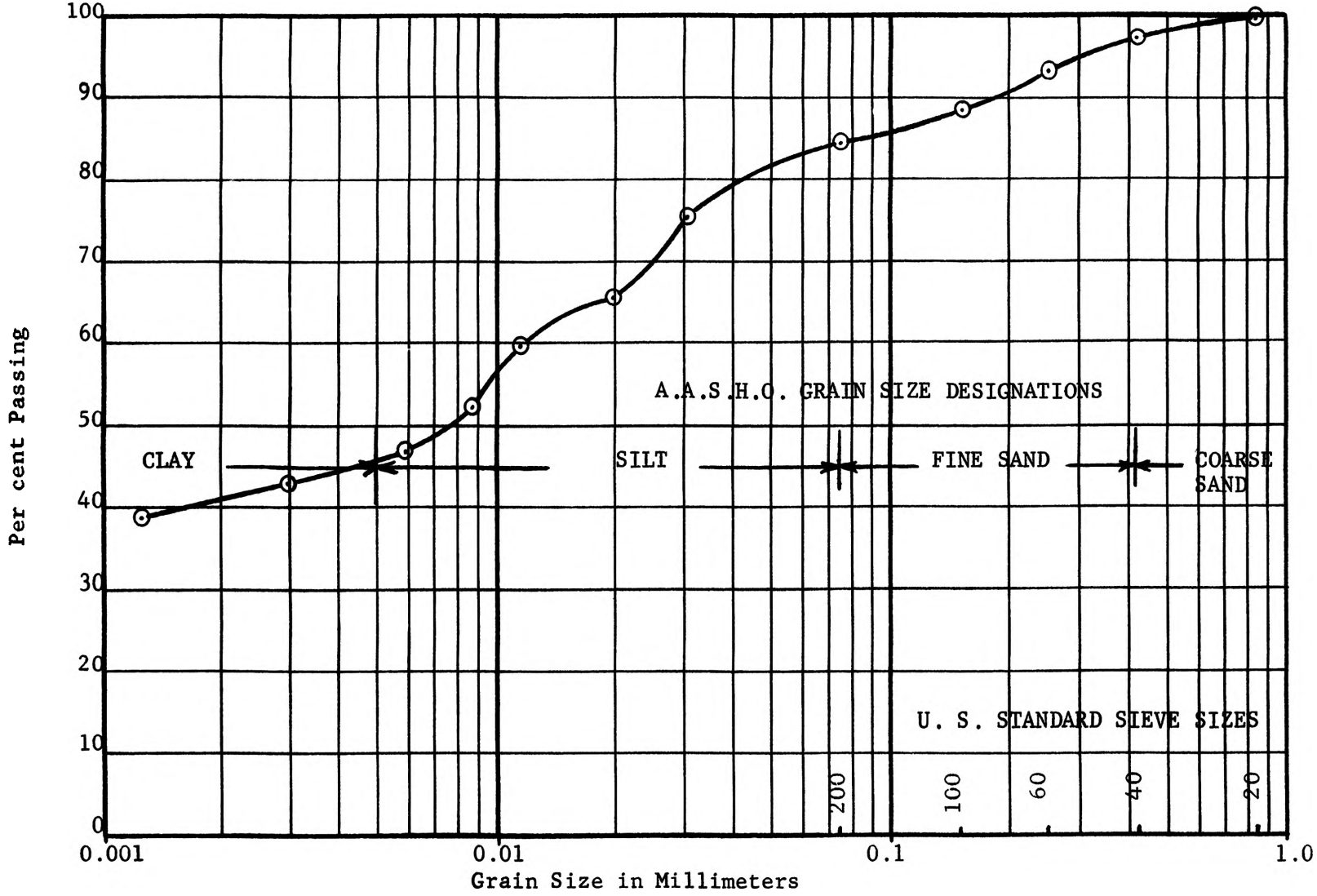


Figure 7 GRAIN SIZE DISTRIBUTION CURVE

The shrinkage tests were conducted using monel shrinkage dishes rather than the usual porcelain dishes due to difficulty encountered in soil adhering to the sides of the porcelain dishes upon drying.

The verbal descriptions of the engineering classifications listed in table I vary somewhat but generally agree that the soil is subject to extremely high volume changes and therefore is unsuitable as a sub-base and provides only a fair to poor subgrade. It is also considered almost impervious.[23]

An X-ray analysis was conducted on the clay (minus the 0.005 mm. size) fraction. Approximately 200 grams of minus number 40 U. S. Standard sieve material were placed in a 1000 cc. beaker filled 3/4 full of distilled water. This was soaked for about 18 hours then washed into a mechanical mixer, mixed for one minute and then washed into a hydrometer jar and settlement was allowed to commence. Stoke's law was used to determine the time of settlement of the desired effective size and the top six inches was extracted from the jar as representing the clay fraction 80 minutes after settlement commenced. This was placed in an evaporating dish and, upon drying, samples were prepared for an x-ray analysis. The closest identification that could be found listed for the clay fraction was that of Burghersdrop clay (a mica montmorillonite)[30]. The probability of this identification being correct was about 50 to 70 per cent.[31] A photograph of the x-ray diffraction pattern is shown in figure 8.

The chemicals selected for evaluation in this study are enumerated in table II. A brief justification of their selection follows.

Diler[19] previously experimented with lime in several forms with Putnam and reported considerable success in so doing. According to

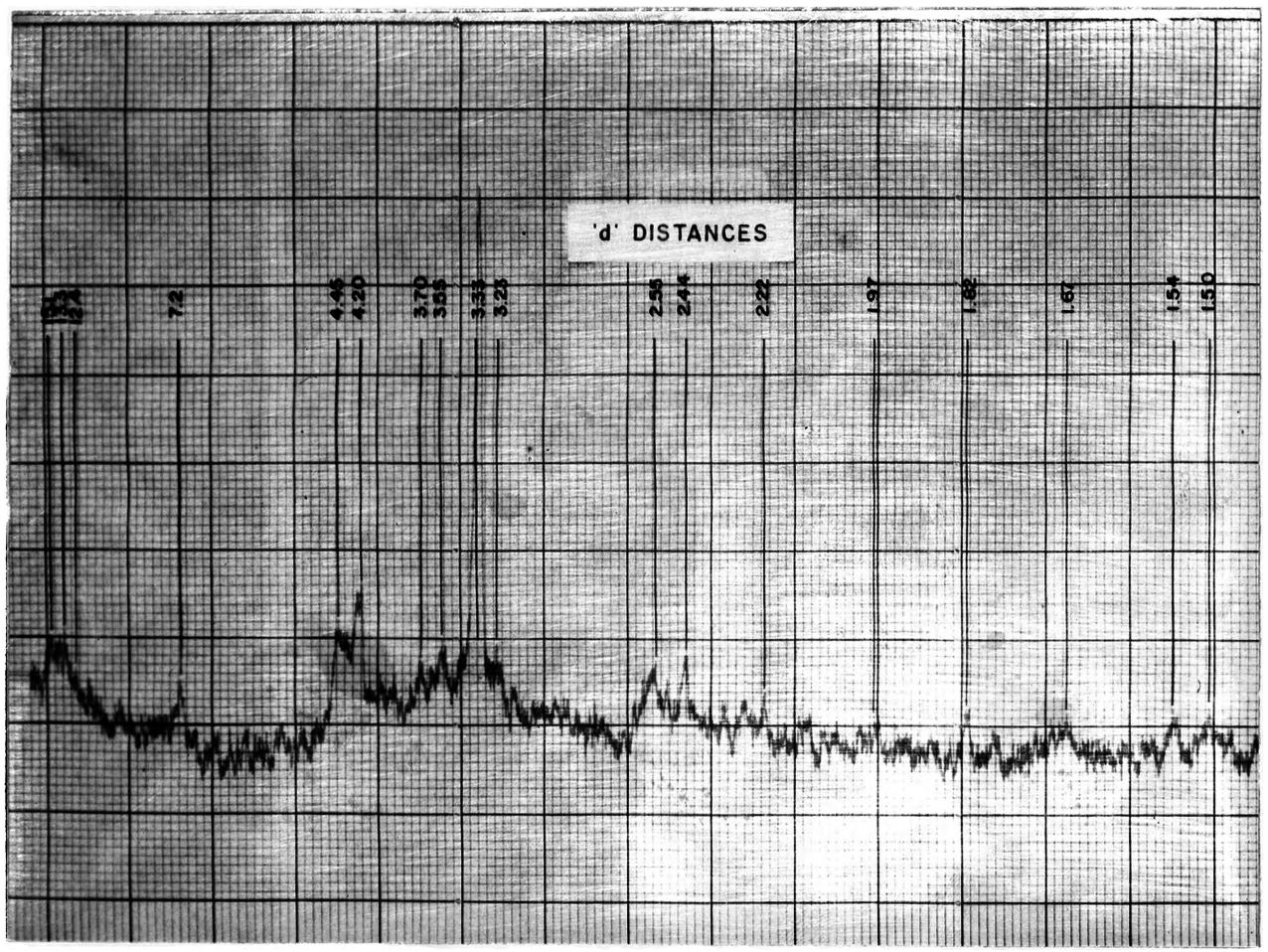


Figure 8 X-RAY DIFFRACTION PATTERN OF CLAY FRACTION OF PUTNAM

Additive	Chemical Formula	Producer	Grade	Cost*
Hydrated Lime	$Ca(OH)_2$	Fisher Scientific Co. Fairlawn, N. J.	Reagent	$20.00/ton[34]
Ferric Chloride	$FeCl_3.6H_2O$	Allied Chemical & Dye Co. New York	Reagent	$0.10/lb. (Estimated)
Sodium Hexametaphosphate	$Na_6P_6O_{18}$	Calgon Co. Pittsburgh, Penn.	Commercial "Calgon"	$0.05/lb. (Estimated)
Sodium Carbonate	Na_2CO_3	Mallinckrodt Chemical Works New York	Reagent	$49.00/ton[34]
Calcium Chloride	$CaCl_2$	Dow Chemical Co. Midland, Michigan	Commercial 94-97%	$49.00/ton[34]
Aluminum Sulphate	$Al_2(SO_4)_3.18H_2O$	Fisher Scientific Co. Fairlawn, N. J.	Technical	$37.00/ton[34]

*Cost refers to commercial grade

Table II SUMMARY OF CHEMICALS EVALUATED

Davidson and Handy[32], lime generally reacts with soils in one or more of three ways. First, it can react with carbon dioxide from the air and form a weak cement in the form of calcium carbonate. This may be somewhat beneficial to soils, however, it is generally prevented in order to more efficiently utilize the calcium ion and develop the best strength. Second, it can benefit a soil by a long-term cementation process occurring between siliceous and aluminous minerals in soils and the added calcium ions (known as the pozzolanic reaction). Third, by cation exchange and electric repulsion, the diffuse layer is decreased and flocculation occurs.

Calcium chloride is chemically classified as a salt and its chief benefit in stabilization is its quality as a dust palliative. In addition, it is thought to lubricate individual soil grains and thereby permit greater compaction at a given compactive effort. It reduces the freezing point of water so it is a valuable agent for use in ice and snow removal.[33] As a chemical stabilizer for a clay soil, it might reduce the diffuse layer either by ion exchange or by repulsion due to a high ion concentration in the porewater and thus result in the sought after flocculation.

Ferric chloride and aluminum sulfate were both selected for their potential as a flocculating agent which might be brought about by either an ion exchange of trivalent iron or aluminum ions for ions of lower valence, or by depression of the diffuse layer. Both chemicals are widely used for sedimentation in the treatment of sewage.

The two chemicals selected as deflocculating agents were sodium hexametaphosphate and sodium carbonate. The addition of sodium ions to the system would tend to enlarge the diffuse layer and thus promote a deflocculant structure. The anions would aid in sequestering the exchanged

ions thus decreasing the potential of the electrolyte, the overall result being a higher zeta potential.

V. DISCUSSION AND RESULTS

The results obtained on the Atterberg limits for each of the chemical additives used are shown graphically (figure 9).

As was pointed out in Chapter I, the complexity of the original substance often causes much conjecture over just what happens when even a fairly simple chemical is added to it. Also, as far as evaluation of the effects of an additive is concerned, the results tend to speak for themselves. Therefore, the discussion of possible causes of the variance in effects of different additives is limited. Further, the chemicals used for this study were selected primarily for their potential cation exchange properties and, since there is no evidence of any other chemical action (such as cementation), the discussion of the initial evaluation of chemical additives can generally be limited to one of cation exchange relationships.

Of the flocculation agents used, hydrated lime had the greatest effect on all of the Atterberg limits and at a strength of eight per cent rendered the soil non-plastic with a shrinkage limit of a little over 20 per cent. Calcium chloride and ferric chloride reduced the liquid limit somewhat; however, no other significant changes were found. Aluminum sulphate produced no significant alteration in any of the Atterberg limits.

The results experienced with hydrated lime were believed to be due to a combination of a cation exchange and depression of the diffuse layer. The probability of the occurrence of cementation by either carbonation or a pozzolanic reaction was considered negligible due to the minute quantity of carbon dioxide present and the short length of time involved between mixing and testing.

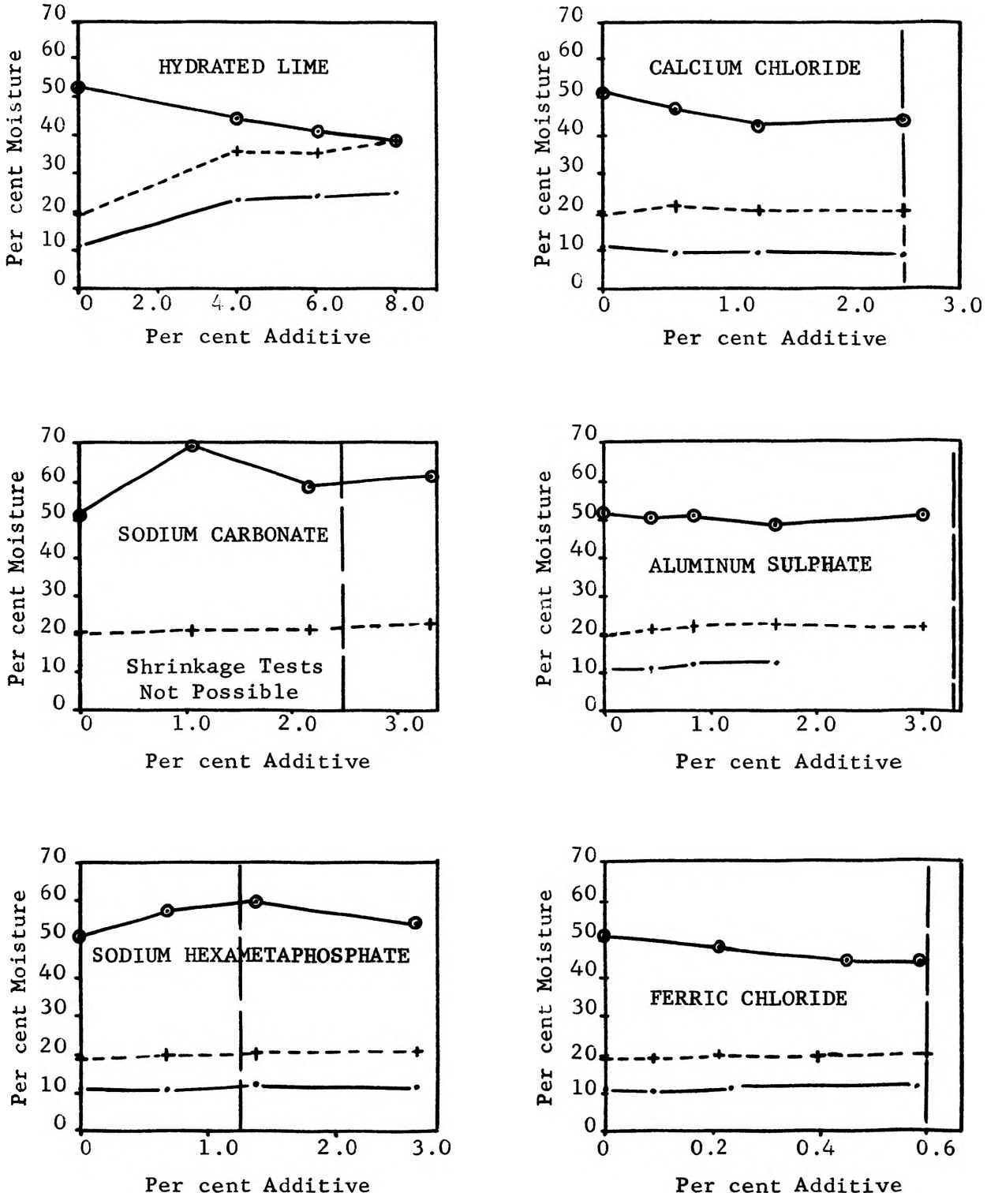


Figure 9 EFFECT OF CHEMICAL ADDITIVES ON ATTERBERG LIMITS

Lack of significant results with the other flocculating agents (calcium chloride, aluminum sulphate, and ferric chloride) can perhaps be attributed to the low quantities used. This may be particularly true in the case of ferric chloride; however, neither calcium chloride nor aluminum sulphate were as beneficial at maximum strengths as was an equal quantity of hydrated lime. Further, the criterion of limiting the quantity of these chemicals to the cost of an amount of lime which was apparently quite effective in stabilizing this soil is a practical matter which this author felt should not be overlooked.

One point of interest in the results of these tests is the better affects from calcium hydroxide than from calcium chloride the latter of which is supposed to be the better ionizer[13]. This leads to the possibility that the $(OH)^-$ anion is perhaps producing the change rather than the Ca^{++} cation.

Both of the agents selected for their deflocculation potential (sodium carbonate and sodium hexametaphosphate) produced results as predicted. Larger liquid limits and plastic indexes were found in both cases. Determination of the shrinkage limit was difficult in the case of Putnam with sodium hexametaphosphate and not even possible in the case of Putnam with sodium carbonate due to the severe breakage of the soil cakes upon drying. All of these results lead to the belief that a deflocculant structure was obtained which was attributed to satisfaction of at least a portion of the surface energy by the addition of the sodium cations with a resulting larger diffuse layer.

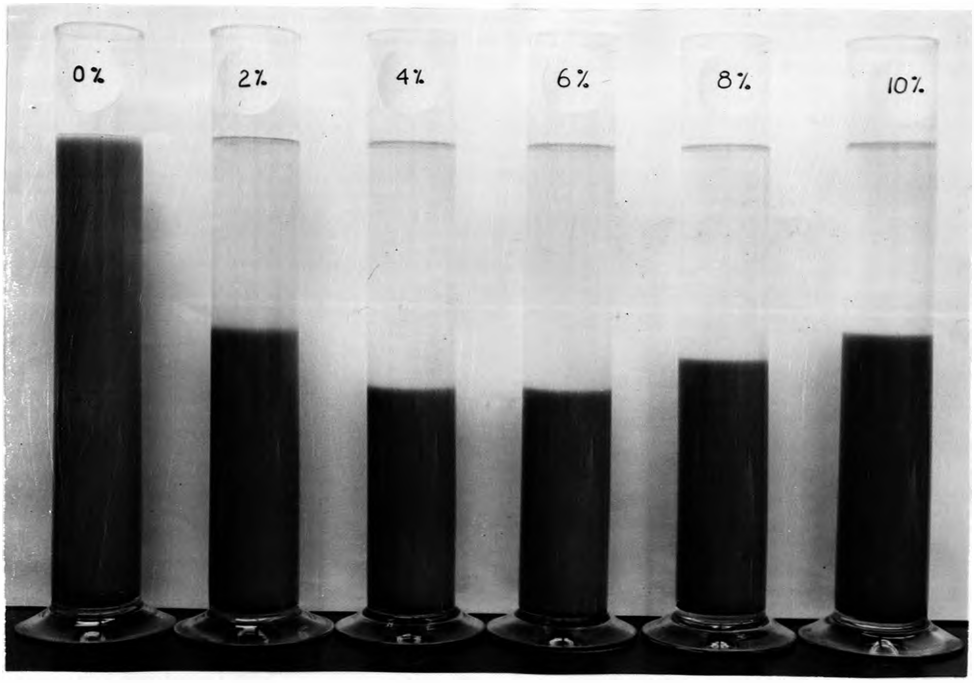
The tests conducted to investigate the concentration versus flocculation or deflocculation tendencies are rather unique and produced interesting results. In figure 10 close examination of the appearance of

the soil in the jars containing lime as compared with the jar of untreated Putnam will show the grainy appearance of the flocculent structure that resulted. Also the optimum quantity can readily be selected as between four and six per cent.

The effect of adding an excessive quantity of deflocculating agent is well illustrated (figure 11). The re-flocculation as strength is increased is thought to be brought about by the increasing ion concentration in the electrolyte causing depression of the diffuse layer. The optimum quantity of sodium carbonate, based upon this test was selected as three per cent. This might appear slightly high in relation to the results depicted in figure 11, however, in this case, the selection was based on a higher uncorrected hydrometer reading in the jar containing Putnam with three per cent additive.

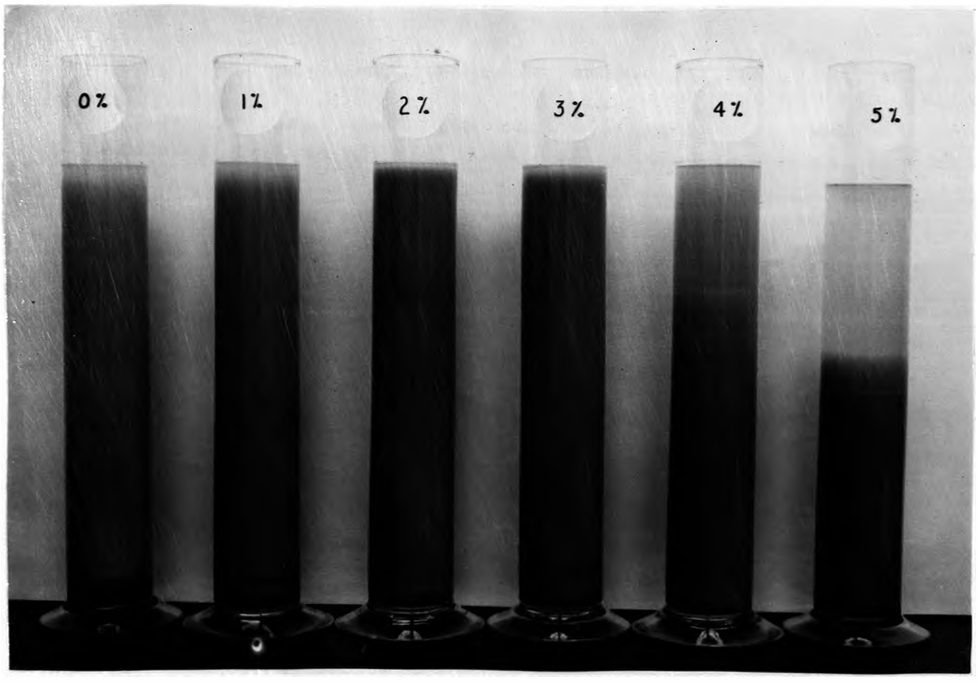
The quantities of chemicals used in the actual swell tests were based on the hydrometer jar tests rather than on the Atterberg tests. This was felt correct in view of the fact that, in the hydrometer jar tests, the soil is free to assume its preferred structure while in the Atterberg tests a certain amount of structure breakdown is caused by the repeated rolling and manipulation of the soil. Also it was felt that the element of human error was more significant in the Atterberg tests.

There are several variable and interrelated factors which affect the swell properties and the measurement thereof. First of all, it is well established that the quantity of moisture and compactive effort will have a pronounced effect in determining the resultant soil density and swelling clay is no exception to this rule. It is also known that swell in a clay soil is a function of the surface energy of the clay mineral. Therefore, the actual amount of swell that occurs must be a function of



COMPARISON OF STRENGTH CONCENTRATIONS OF
HYDRATED LIME IN FLOCCULATION OF PUTNAM
(10 Minutes After Mixing)

Figure 10



COMPARISON OF STRENGTH CONCENTRATIONS OF
SODIUM CARBONATE IN DEFLOCCULATION OF PUTNAM
(24 Hours After Mixing)

Figure 11

the volume of soil present. It should also be appreciated that in a rather loose mass of soil, swell of individual particles can occur within the void space thereby reducing the apparent amount of swell. Thus, initial density, which is determined by the moisture content and compactive effort, is both directly and inversely related to the measured swell which occurs under a moist environment.

While it would be best to hold all but one factor to a constant value and then be able to accurately measure and relate the remaining factors, this procedure was not entirely possible due to the equipment available and the time required for the larger number of such tests that would be necessary in order to be able to actually compare the overall effects of the chemical additives. Further, the objective was not so much an accurate measurement of the effects of one additive as it was the comparison of several additives.

With this in mind, the author conducted the swell tests in the manner outlined in Chapter III. A total of 36 tests were conducted, 12 on the untreated soil, 12 on the soil treated with three per cent sodium carbonate, and 12 on the soil treated with five per cent calcium hydroxide. Two of the test results were rejected due to disturbance of the equipment. With each group, moisture contents and compactive efforts were varied. The quantities of chemicals used were based on the calculated oven-dry weight of the soil and the chemical was mixed with the air dry soil prior to adding moisture.

All possible precautions were taken with the equipment used in an attempt to reduce errors in test procedures to a minimum. All metal to metal surfaces were lightly greased prior to assembly either to provide a moisture barrier or to reduce friction. Any slight disturbance of the

strain gages and position of the fulcrums on the piston rods would effect the dial readings by as much as 0.003 of an inch and thereby produce an error in apparent swell of 0.5 per cent. It should also be stated that inaccuracies are expected to be more prevalent with the small size of equipment used.

The results of the swell tests are tabulated in tables III, IV and V, and illustrated graphically in figures 12 through 16 (Appendix A). Considerable difficulty was encountered in determining the best way to relate and graph the results obtained because of allowing the variation of several of the related factors involved in measuring swell. This was further aggravated by the inaccuracies of the equipment as stated above.

Figure 12 shows the relationship between moisture content at compaction and the per cent swell. A major point brought out in this graph is the relationship in the swell characteristics of Putnam and Putnam in combination with the two selected chemicals. The deflocculating agent raised the swell tendencies somewhat while with the hydrated lime, a few slight reductions in volume were recorded but there was absolutely no swell. Also it is evident that the apparent swell is substantially reduced for Putnam treated with sodium carbonate by increasing the initial moisture content.

It would seem that points plotted for such a graph would result in far more scatter than is shown because density is not taken directly into account. The points thus plotted do, however, take density into account in a rather indirect manner for as the moisture content increases, the density generally increases with the same compactive effort up to the optimum moisture content after which the density generally starts to decrease. Thus, considering only the density, it would seem that the swell

must increase and then decrease as the moisture content increases. As can be seen, this is not the case, however, and it is therefore concluded that apparent swell is uniquely related to the initial moisture content which manifests itself more in the satisfaction of the surface energy than in density.

In order to further investigate this idea, figures 13 through 16 were devised in order to directly relate density with swell. In figures 13, 14, and 15, initial dry density is related to the final moisture content. The most important points brought out by these graphs are that the final moisture content is significantly altered by chemical treatment of Putnam and that with untreated Putnam or with Putnam treated with a deflocculating agent, the final moisture content is in every case above the plastic limit.

The scatter produced by the points plotted is explained by the fact that all points which fall above the lines were compacted dry of optimum while those points which fall below the line were compacted on the wet side of optimum. Their deviation from the line illustrates that initial moisture content is a fairly important factor in determining the final moisture content. Thus, the final moisture content is dependent upon both density and upon initial moisture content.

In figure 16, per cent swell is rather uniquely related to density and the moisture content required to saturate the original sample subtracted from the final moisture content. With the aid of the graphs in figures 13, 14, and 15, the per cent of apparent swell can be estimated within reasonable limits if the initial moisture content and the density are known. However, it is not the intent here to arrive at an equation to predict per cent swell but to show the correlation between density, various moisture contents and per cent swell.

An overall analysis of the results of the swell tests conducted show that swell resulted in either the natural Putnam or in Putnam treated with sodium carbonate regardless of the initial density at which it was compacted. Further, the quantity of apparent swell in these soils was appreciably reduced as the moisture content at compaction was increased. However, manipulation of such a soil is accomplished only with difficulty in the laboratory but must be next to impossible in the field. The alternative would be to place the soil in a drier state and compensate for the swell to take place. It was found in the tests conducted, however, that eventually, under a moisture environment, the moisture content increased with the swell to a point where the soil was again above the plastic limit. The tests conducted with Putnam in combination with sodium carbonate demonstrate very well the detrimental results that can probably be expected from a treatment of this type.

The fact that treatment of Putnam with five per cent hydrated lime eliminated the swell characteristics is attributed to the resultant reduction in demand for moisture. Further, it can be seen that in no case did the moisture content of this soil increase above the plastic limit and only in one very loosely compacted sample did it come closer than to within about five per cent of the plastic limit (figure 15). It should also be noted that in this flocculant structure, at equal moisture content for compaction, the resultant mass is less dense and will therefore adsord more water in the voids (figures 13 and 15).

These results tend to support the concept regarding the importance of satisfying the surface energy of a clay soil in order to reduce its swell and also improve its other engineering characteristics.

The results of the tests conducted with untreated Putnam can be related to some of the difficulty encountered in Missouri highways constructed on this soil. The tendency for such highways to lose their support at edges and joints can be attributed to the higher quantity of moisture available in these areas. This tendency, coupled with the "working" of the affected soils by the resultant higher deflections of the slab, further enhance the adsorption capability of the soil by causing the soil to break down into its preferred (deflocculent) structure. The effects on the engineering characteristics of this degeneration should be obvious. Further it is evident that no amount of physical manipulation will solve this problem but that chemical stabilization would probably eliminate it.

VI. CONCLUSIONS AND RECOMMENDATIONS

The objectives of this study were as stated in the introduction. With these objectives in mind, a review of literature was undertaken and a series of tests conducted, the results of which suggest the following conclusions:

1. The surface energy concept as explained in chapter II is a very useful tool in analyzing a swelling clay soil.

2. Swell of an untreated or deflocculated Putnam soil is a unique function of initial moisture content with the dry density exhibiting far less significance.

3. Untreated Putnam will not exhibit desirable engineering characteristics regardless of the physical manipulation at placement, however, its swell properties at a load of 1.25 psi can be greatly improved by placement at a moisture content at or above 22 per cent.

4. Chemical additives which tend to deflocculate Putnam soil are not generally considered advisable.

5. Hydrated lime at five per cent concentration will eliminate the swell properties of Putnam under a load of 1.25 psi. Further, this chemical will greatly improve the overall engineering properties of this soil.

6. The hydrometer jar tests are a better and quicker measure of a chemical additives effect as a flocculating or deflocculating agent than are the Atterberg tests.

7. The Hogentogler consolidometer and the compacting device used in this study produce sufficiently accurate results for comparison of the effects of chemical additives on a swelling soil.

Recommendations for further study previously brought out in the body of this manuscript are summarized as follows:

1. Many more chemicals might be tested as stabilizing agents for Putnam, however, it is probably best to consider only those chemicals classified as flocculating agents.

2. Test chemicals which will determine the effect of the OH^- anion in the stabilization of Putnam.

3. Conduct swell tests at varying loads in order to evaluate the effect of this aspect on the swell properties of Putnam.

4. Conduct further chemical analyses of Putnam in order to aid in selection of chemical stabilizers and understand the mechanisms by which these chemicals affect the soil.

APPENDIX A

RESULTS OF SWELL TESTS

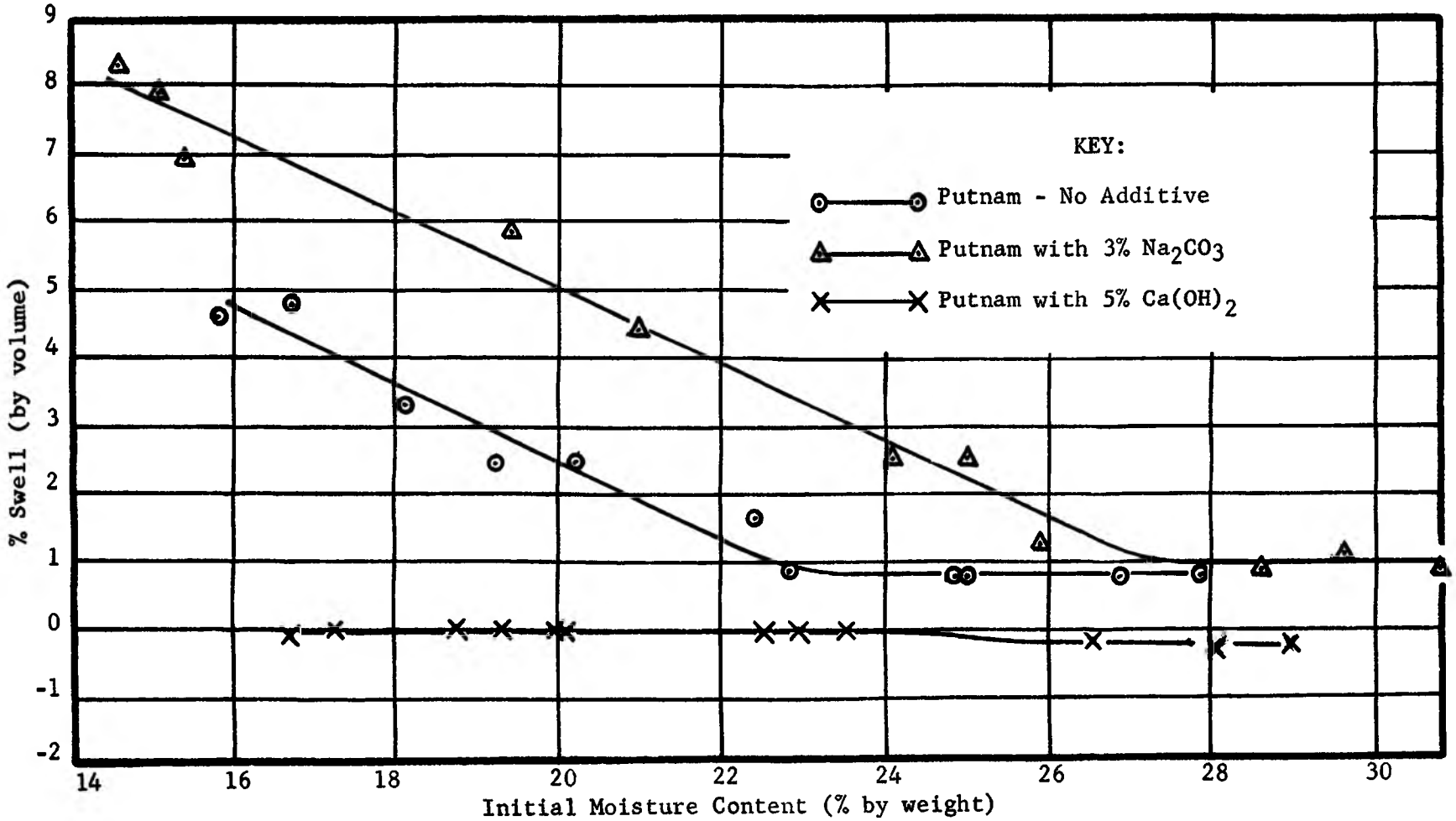


Figure 12 EFFECT OF INITIAL MOISTURE CONTENT ON SWELL OF TREATED AND UNTREATED PUTNAM

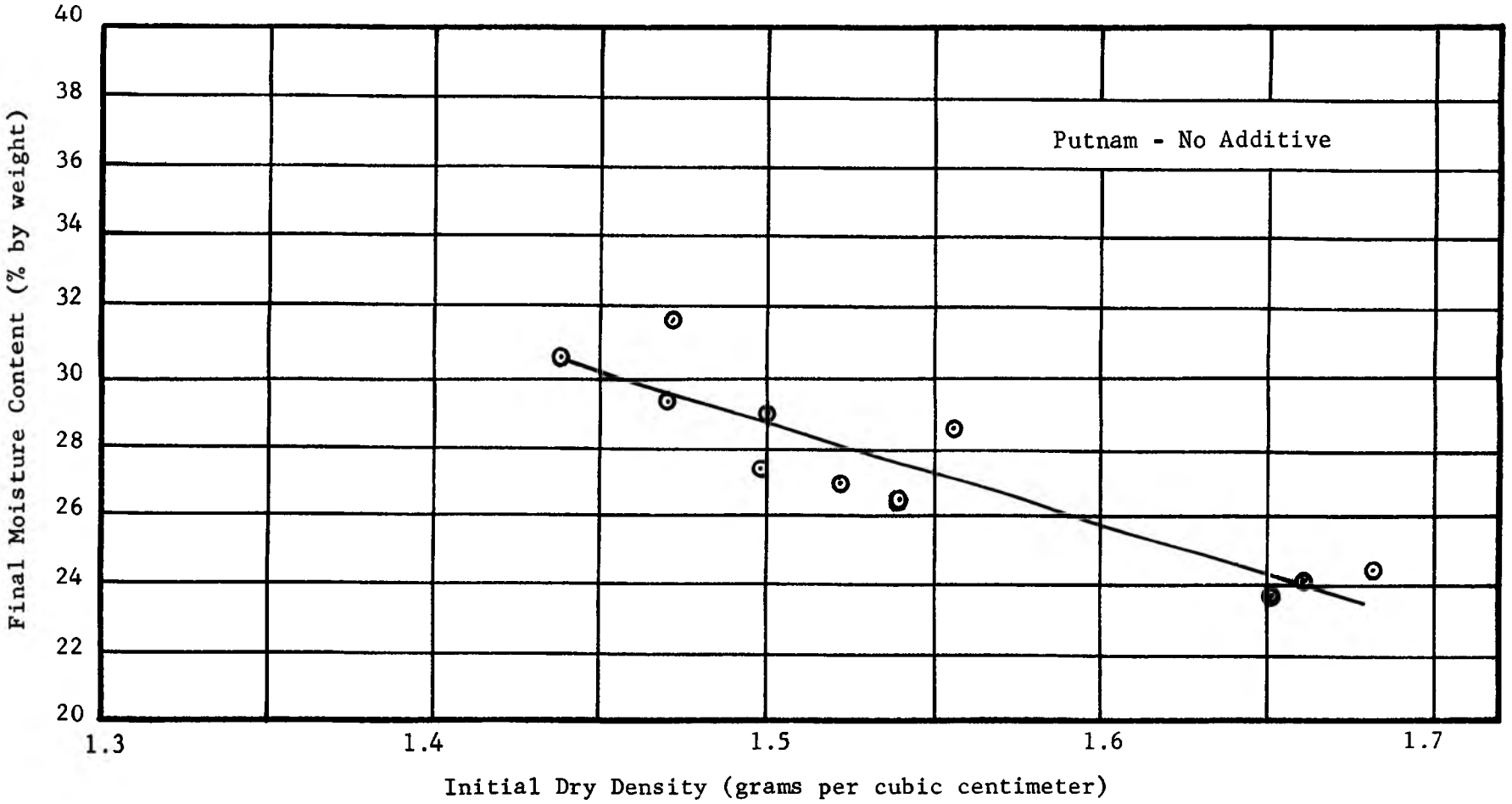


Figure 13 FINAL MOISTURE CONTENT VS. INITIAL DRY DENSITY FOR UNTREATED PUTNAM

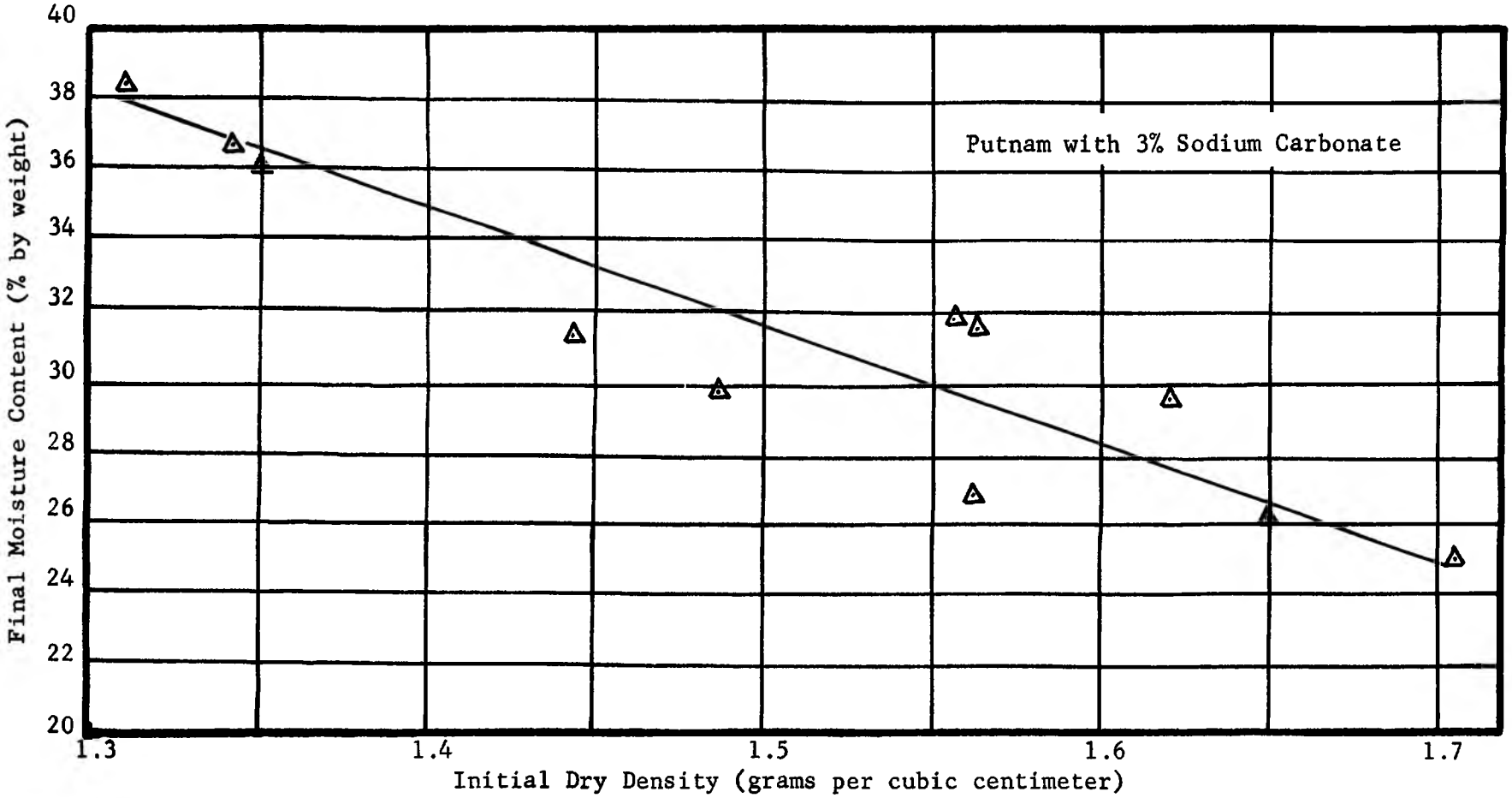


Figure 14 FINAL MOISTURE CONTENT VS. INITIAL DRY DENSITY FOR PUTNAM TREATED WITH 3% SODIUM CARBONATE

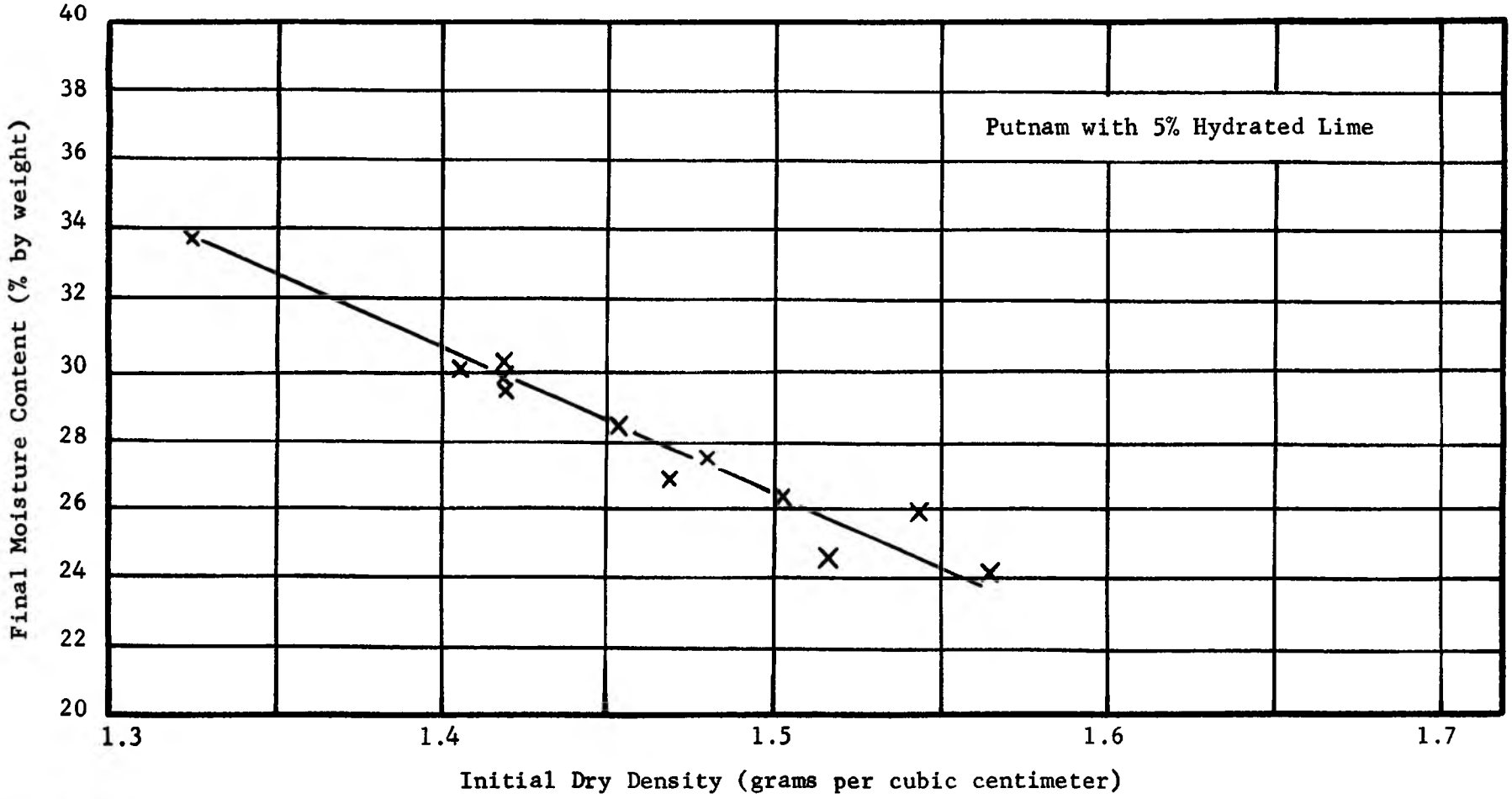


Figure 15 FINAL MOISTURE CONTENT VS. INITIAL DRY DENSITY FOR PUTNAM TREATED WITH 5 PER CENT HYDRATED LIME

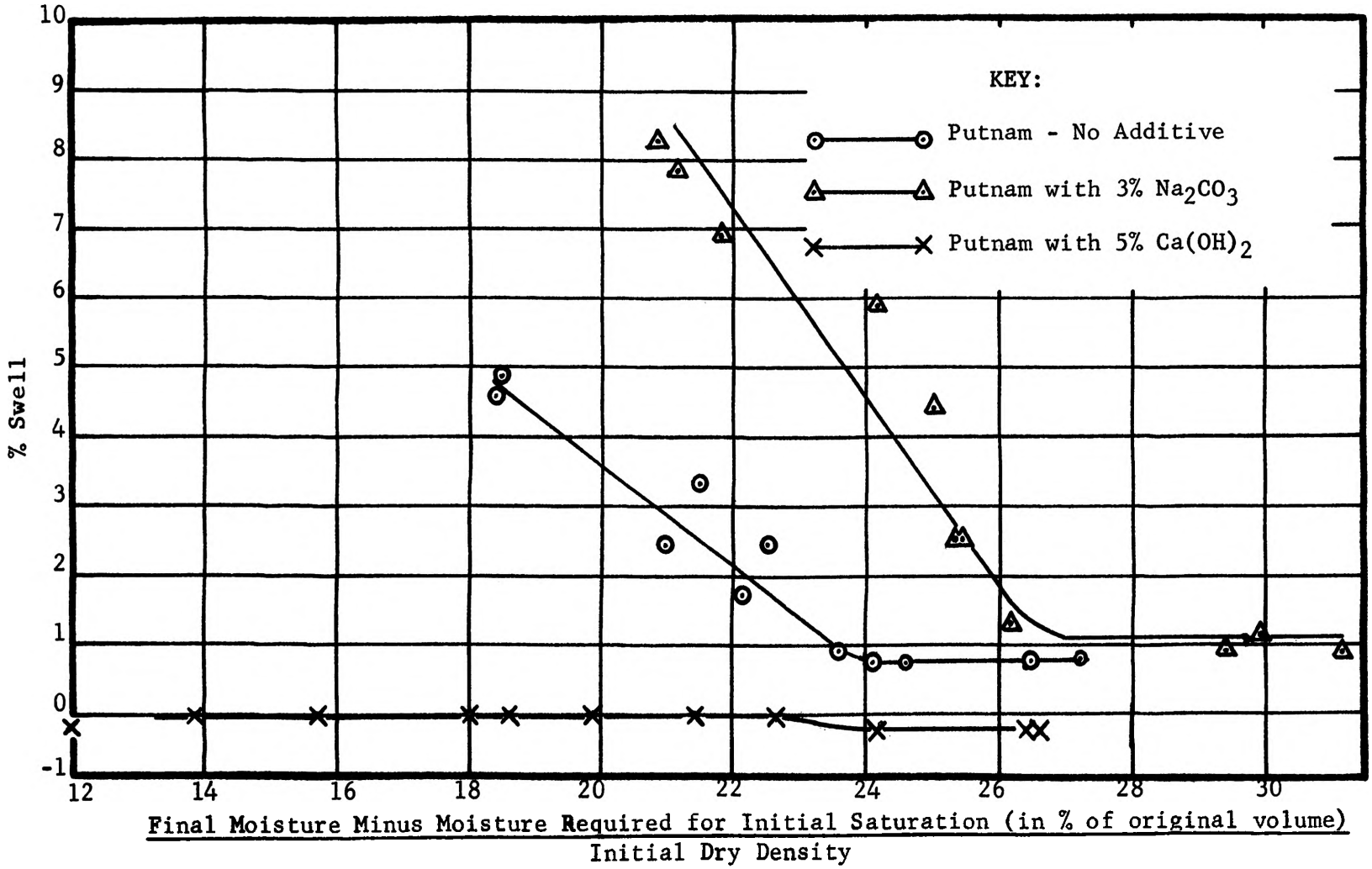


Figure 16 PER CENT SWELL OF TREATED AND UNTREATED PUTNAM RELATED TO VARIOUS MOISTURE CONTENTS AND DENSITY

TEST NUMBER		1	2	3	4	5	6	7	8	9	10	11
Initial Wet Wt	(gms)	48.9	46.7	53.5	54.2	54.0	50.0	48.7	50.7	50.6	51.9	52.1
Final Dry Wt	(gms)	42.2	40.0	44.9	45.1	45.7	40.7	39.0	41.4	39.9	40.6	41.7
Init Wt Moist	(gms)	6.7	6.7	8.6	9.1	8.3	9.3	9.7	9.3	10.7	11.3	10.4
Init % Moist		15.8	16.7	19.2	20.2	18.1	22.8	24.8	22.4	26.8	27.8	24.9
Vol of Solids	(cc)	16.22	15.40	17.28	17.34	17.58	15.68	15.00	15.92	15.35	15.63	16.02
Vol of Voids	(cc)	10.94	11.76	9.88	9.82	9.58	11.48	12.16	11.24	11.81	11.53	11.14
Final Wt Moist	(gms)	12.0	12.6	10.7	10.9	11.1	11.8	11.9	11.1	11.7	11.3	11.0
Final % Moist		28.4	31.5	23.8	24.2	24.3	29.0	30.5	26.8	29.3	27.8	26.3
Moist to Sat Orig Vol	(gms)	4.24	5.06	1.28	0.72	1.28	2.18	2.46	1.94	1.11	0.23	0.74
Init Dry Density	(gms/cc)	1.557	1.472	1.652	1.662	1.683	1.500	1.438	1.524	1.470	1.498	1.540
Per Cent Swell		4.57	4.80	2.43	2.43	3.28	0.86	0.69	1.57	0.69	0.69	0.69

Table III RESULTS OF SWELL TESTS - PUTNAM WITH NO ADDITIVE

TEST NUMBER		1	2	3	4	5	6	7	8	9	10	11
Initial Wet Wt	(gms)	50.8	48.6	48.7	54.1	45.5	55.2	44.7	52.6	48.0	50.8	51.8
Final Dry Wt	(gms)	44.0	42.2	42.5	44.7	36.4	46.2	35.5	42.4	36.7	39.2	40.3
Init Wt Moist	(gms)	6.8	6.4	6.2	9.4	9.1	9.0	9.2	10.2	11.3	11.6	11.5
Init % Moist		15.4	15.1	14.6	21.0	25.0	19.4	25.9	24.1	30.8	29.6	28.6
Vol of Solids	(cc)	16.92	16.22	16.32	17.20	13.99	17.78	13.65	16.30	14.10	15.07	15.50
Vol of Voids	(cc)	10.24	10.94	10.84	9.96	13.17	9.38	13.51	10.86	13.06	12.09	11.66
Final Wt Moist	(gms)	13.0	13.4	13.4	11.7	13.3	11.6	13.6	11.4	13.2	12.2	12.0
Final % Moist		29.6	31.8	31.5	26.2	36.6	25.1	38.3	26.9	36.0	31.2	29.8
Moist to Sat Orig Vol	(gms)	3.44	4.54	4.64	0.56	4.07	0.38	4.31	0.66	1.76	0.49	0.16
Init Dry Density	(gms/cc)	16.20	15.58	15.66	16.48	13.42	17.04	13.10	15.62	13.50	14.43	14.86
Per Cent Swell		6.89	7.81	8.25	4.39	2.50	5.83	1.25	2.50	0.86	1.04	0.86

Table IV RESULTS OF SWELL TESTS - PUTNAM WITH 3% SODIUM CARBONATE

TEST NUMBER		1	2	3	4	5	6	7	8	9	10	11	12
Initial Wet Wt	(gms)	48.8	47.7	42.0	45.8	48.2	50.7	46.9	47.6	51.5	49.7	50.6	50.6
Final Dry Wt	(gms)	41.1	40.7	36.0	38.2	40.1	42.5	38.5	38.5	41.9	38.5	39.5	40.0
Init Wt Moist	(gms)	7.7	7.0	6.0	7.6	8.1	8.2	8.4	9.1	9.6	11.2	11.1	10.6
Init % Moist		18.7	17.2	16.7	19.9	20.2	19.3	22.4	23.6	22.9	29.1	28.1	26.5
Vol of Solids	(cc)	15.82	15.00	13.27	14.70	15.43	16.33	14.80	14.80	16.10	14.81	15.20	15.40
Vol of Voids	(cc)	11.34	12.16	13.89	12.46	11.73	10.83	12.36	12.36	11.06	12.35	11.96	11.76
Final Wt Moist	(gms)	10.1	10.7	12.2	11.5	11.1	10.3	11.6	11.5	10.9	11.4	11.3	10.8
Final % Moist		24.6	26.3	33.9	30.1	27.6	24.2	30.2	29.9	26.0	29.6	28.6	27.0
Moist to Sat Orig Vol	(gms)	3.64	5.16	7.89	4.86	3.63	2.63	3.96	3.26	1.46	1.15	0.86	1.16
Init Dry Density	(gms/cc)	1.518	1.501	1.327	1.408	1.480	1.565	1.420	1.420	1.540	1.420	1.455	1.472
Per Cent Swell		0	0	-0.17	0	0	0	0	0	0	-0.17	-0.17	-0.17

Table V RESULTS OF SWELL TESTS - PUTNAM WITH 5% CALCIUM HYDROXIDE

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VITA

Dale Eugene Dobson was born on March 25, 1930, in Marshalltown, Iowa, the son of Donald W. and Ona M. Dobson. His primary and high school educations were accomplished in the public school system in Marshalltown and he graduated from Marshalltown High School in June 1948.

He enrolled at Iowa State College in September, 1948 and received a bachelor of science degree in civil engineering from that institution in June 1953. At the same time he was commissioned a Second Lieutenant in the United States Army Reserve.

Upon graduation, he was called into the service in the Corps of Engineers and has been on continuous active duty since that time. His military assignments, except for schools, have involved duty at Fort Carson, Colorado; Korea; Fort Leonard Wood, Missouri; Fort Polk, Louisiana; Libya and Washington, D. C. Military schools attended were, the Engineer Officers Basic Course and the Engineer Officers Career Course, both at Fort Belvoir, Virginia and training as a fixed and rotary-wing aviator at Fort Rucker, Alabama. He was commissioned a Regular Army Captain in December of 1961.

Captain Dobson was married to the former Helen Louise Knodle of Marshalltown, Iowa, in 1952, and has one son, Joseph Brian, and two daughters; Sarah Lynn, and Martha Helen.